CSCE 436/836: Embedded Systems
Lab 1a: Hovercraft Construction and Experiments

Instructor: Carrick Detweiler
carrick _at_ cse.unl.edu
University of Nebraska-Lincoln
Spring 2011

Started: Jan 20, 2011
Lab 1 Due: Feb 3, 2011
Lab 1a Recommended Completion Date: Jan 27, 2011

1 Overview

This is the first part (a) of Lab 1. In this lab you will design, construct, and perform experiments with the physical hovercraft. In the second part (b) of this lab, you will learn to program the hoverboard embedded system that we will use to control the hovercraft. In future labs we will use the information you collect to calibrate controllers you will develop on the hoverboard embedded system.

Before starting you should read through the whole lab. Some parts can be done in parallel, while some sections rely on the completion of previous sections. You should discuss your plan of attack for the lab in your group and decide how you will work together and divide the work. Everyone, however, is responsible for knowing about all sections of the lab.

2 Materials

The main materials you will use in this part of the lab to construct the hovercraft are:

- Sheet of 1.5 inch think rigid foam insulation
- 5mil plastic sheet
- Six GW/EDF40 Ducted Fans (thrusters)
- Wire, tape, brackets, screws, etc.

You will also use a various hand tools including knives, soldering irons, power supplies, etc.

3 Safety

In this lab you will be using a number of tools and devices that can be dangerous if mishandled. You should always follow instructions, think twice, and ask for help if you are unsure what you are doing or are unsure about safety. Please report any accidents to the course staff and seek medical attention immediately if needed. Reasonable precautions will prevent most accidents. Do not work in the lab alone or when you are tired.

Throughout this course you will be using ducted fans for propulsion of the hovercraft. These are relatively safe, but you should never put your fingers or anything else inside of them. Along these lines, if you have long hair, you should make sure to tie it back or cover it while in the lab.

We will also be using power supplies and batteries in this course. Make sure to follow instructions when using these devices as they can be dangerous if misused. You should always be careful not to short wires on batteries or power supplies and follow appropriate methods for charging batteries.

Finally, in this lab you will be using sharp knives and soldering irons. These can cut or burn you or your classmates. Always be aware of your surroundings when using these devices and never cut towards yourself or anyone else.

4 Hovercraft Design and Construction

In this section you will design and construct your hovercraft. The exact configuration will be left up to you. The only constraint is that the hovercraft must be omni-directional (able to translate in any direction) and it must have rotational control (ideally equal control clockwise and counterclockwise).

One of your goals in designing and constructing your hovercraft is to make it look nicer than mine. This shouldn't be too hard :)

4.1 Base

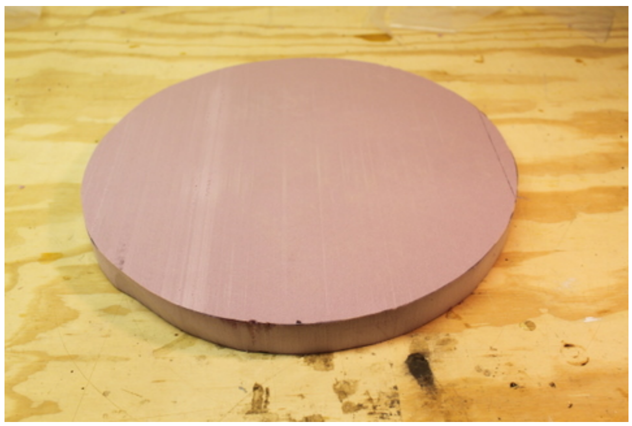

Figure 1: A foam circle cut out of the sheet of rigid foam.

For the base we will be using 1.5 inch rigid foam insulation. This is a lightweight material that is easy to work with and relatively inexpensive. There are a variety of circle templates that you can use ranging from about 12 inches to 17 inches in diameter. You are free to make your hovercraft whatever diameter you choose. The only constraints are that it should be larger than 10 inches in diameter and no more than 20 inches. You can also create other shapes, although I suggest you cut a circle as it makes creating a good skirt significantly easier.

To cut the foam, first lay your template circle on top of the foam. Select a portion of the foam that will result in as little wasted foam as possible. Trace a circle on the foam with a pen or marker. Remove the template and then carefully cut the foam out using provided knife. When using the knife extend the blade to a length slightly longer than the width of the foam and then use the locking nut to lock the blade in place. Make sure to keep the blade perpendicular the surface to ensure a clean cut. Small sawing motions may be helpful. Note, **you should cut the foam over the plywood or off the edge of the table so that you do not cut into the workbenches.** Also, it may be helpful to do a rough cut first (minimizing waste) so that you can maneuver the piece of foam more easily.

Figure 1 shows the end result. Having a perfect circle is not critical, but you should trim off any large errors. You can always make a slightly smaller circle if you mess up the first cut.

Question: What diameter hovercraft base did you decide to use? What was your reasoning?

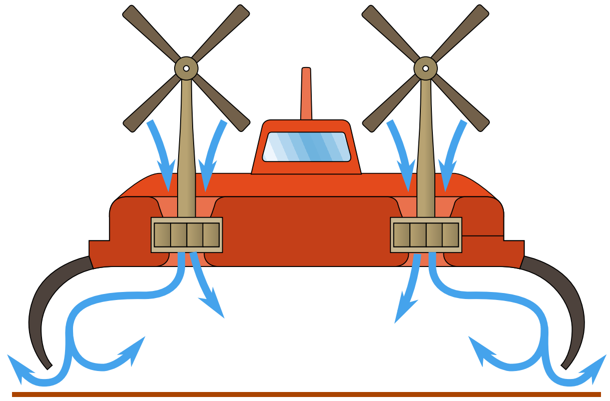

Figure 2: A flexible walled skirt design. Air flows down into the skirt and inflates it. Most air remains inside and recirculates. A small amount of air leaks out and provides the air cushion (Image modified from original on wikipedia.org hovercraft entry).

4.2 Skirt

The skirt is the most critical component of a hovercraft. There are multiple types of skirts including bag skirts, wall skirts, and finger skirts (roughly ranging from easiest to hardest to build). The goal of all skirt designs is to provide a small cushion of air under the hovercraft, while adapting and conforming to any irregularities in the surface. If the surface were perfectly smooth (think about air-hockey tables), you wouldn't need a skirt, you could just pump air under the hovercraft and it would create a nice cushion. In practice most surfaces are somewhat irregular, so the skirt needs to be flexible enough to adapt to the surface, yet strong enough to hold in the air pressure.

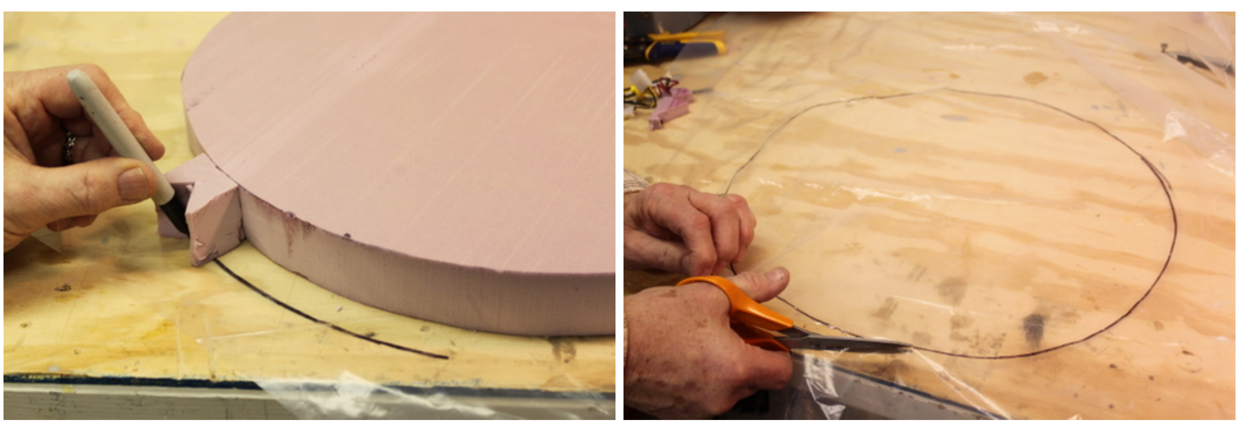

Figure 3: (left) Using a spacer to draw on the plastic. (right) Cutting the plastic.

A bag skirt is like putting an inner-tube under the hovercraft and putting some holes in it on the bottom. Air flows out of the holes to provide a cushion of air and the inner-tube conforms to the surface. A wall skirt (the type we will be using, shown in Figure 2) is basically a flexible wall going around the hovercraft that keeps the air in and conforms to the surface. A finger skirt consists of large number of small triangular segments and is similar to the wall skirt except it is able to handle a more varied terrain as each segment of the skirt is more flexible and independent of the other segments.

To construct a wall skirt we will use 5mil plastic sheeting. Through experimentation I found that this particular type and thickness plastic resulted in a good skirt for this size hovercraft. Start by laying the foam you cut on top of the plastic. Create a spacer out of scrap foam to help you guide drawing a circle that is approximately 0.75 inches larger than foam circle as show in Figure 3. Then cut out the plastic circle.

Figure 4: Taping the plastic disk to the hovercraft base.

The next step is to tape the plastic to the bottom of the hovercraft. Place the foam over your plastic cutout and center it. Now, fold up the plastic, it should come about half way up the edge of the foam. As shown in Figure 4, tape the skirt all around the hovercraft. The tape will extend slightly higher than the top of the foam, fold this down all around. Assure that the tape is well adhered to the foam all the way around. The plastic should now completely cover the bottom of the hovercraft. When taping, the plastic does not need to be completely tight to the base, but it should have relatively even tightness all the way around.

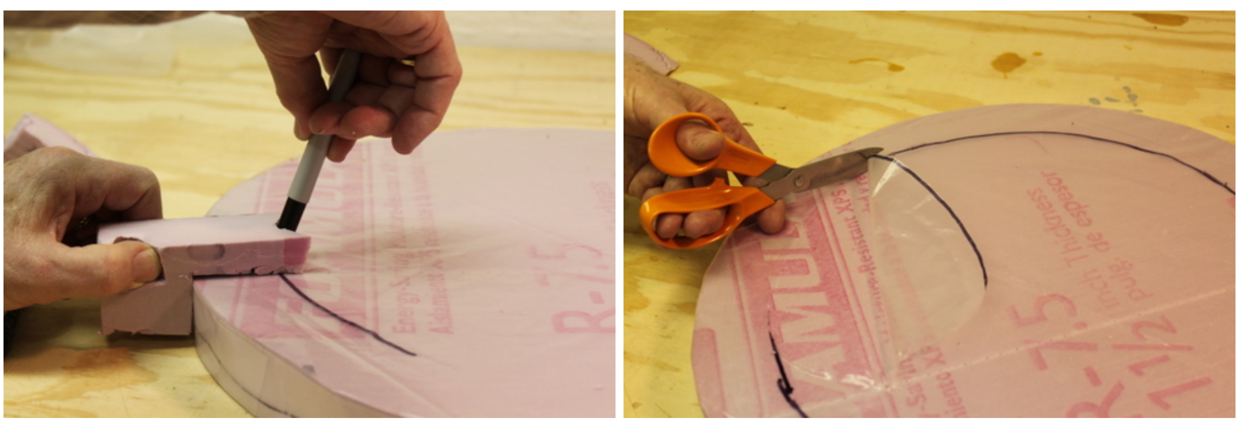

Figure 5: (left) Marking the inside of the plastic with a spacer. (right) Cutting the inside of the plastic to form the skirt.

The next step is to mark and cut a circle out of the center of the skirt. This will leave a annulus of plastic around the edge of the hovercraft, forming the skirt. Again, create a guide using left over foam as shown in Figure 5. You should size it such that there will be about 1.5 inches of plastic remaining. Then cut out the inner circle. Try to cut smoothly, as this will be the edge of the skirt. Figure 6 shows the resultant skirt.

Note that you may want to experiment with the efficiency of the skirt and lift (described in Section 5) before completing the final thruster layout in the next section. You will, of course, have to install the lift thruster first.

Figure 6: The resulting skirt.

Question: Describe the construction of the skirt and any problems you encountered. Did your first skirt work as expected?

4.3 Thruster Layout

In this section we will come up with a layout for the thrusters. The hoverboard supports a total of six thrusters. One will be used as the lift thruster. The remaining five can be positioned in any configuration.

4.3.1 Lift Thruster

Start by installing the lift thruster. To do so, find the center of your hovercraft. Hold the small end of the thruster over the center of the hovercraft. Trace this using a pen or marker and cut out the foam. Note that the hole should be slightly small so that friction will hold the thruster in the hole. It is best to start with a smaller hole, as it is easier to make it larger later[1]. Slide the small end of the thruster into the hole. At this point you should probably verify that your skirt works properly by doing Section 5.

4.3.2 Motion Thrusters

You have 5 remaining thrusters to use to control the hovercraft. The layout of these is up to you. However, your hovercraft must be omni-direction (must be able to translate in any direction without needing to rotate first). In addition, you should have rotational control. Note that the thrusters can only operate in one direction (they can only push, not pull).

There are a couple of configurations you can use to achieve omni-directional and rotational control. One idea is to have three translational thrusters (120° separation) and two opposing rotational thrusters. To move in some directions, you will have to use multiple thrusters. You could also use four translational thrusters (±x, ±y) and one rotational thruster. With this configuration you may only be able to rotation in one direction quickly, but you could potentially utilize the torque from the lift thruster to rotate in the other direction. Finally, you could place some of the translational thrusters at a slight angle so they would exert a torque on the craft and produce a rotation. The choice is up to you. It is easy to reconfigure the thrusters, so you can try a variety of setups.

Question: What thruster configuration did you decide to use (a picture may be useful)? Why did you choose this?

To mount the thrusters we will use 1.5 inch copper pipe hangers and screws as shown in Figure 7. These to not fit exactly, however, you can pliers to form them to the thrusters. You should make sure that they

[1] If you do happen to make it too large, you can create another hole in a different location as the lift thruster does not need to be exactly in the center. Cover over your old hole with tape

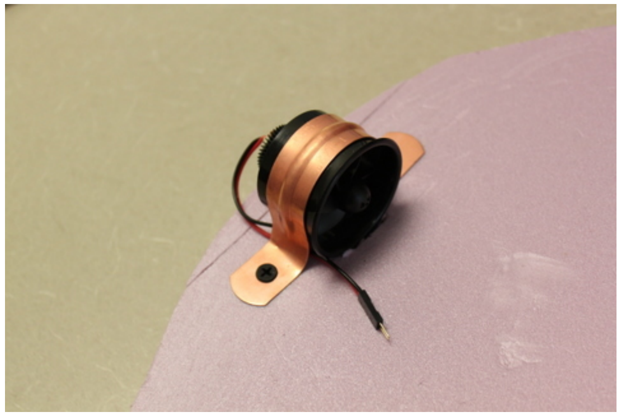

Figure 7: The mounted thruster.

hold the thrusters tight against the hovercraft, but that they do not deform the thruster housing as this will impede the thruster. You can cut a small channel or press the lip of the thruster into the foam to help lock it in place. Use the 1.25 inch drywall screws to secure the bracket. Do not tighten them too much as the foam is soft and you will easily strip the hole.

Once you have soldered extension wires onto the thrusters (in the next Section), you can bury the wires in the foam to keep them out of the way. To do so, cut a small channel in the foam. Place the wires in the channels and then tape over them to keep them inside.

4.4 Soldering Thruster Wires

The wires on the thrusters are too short to reach a single location where the hoverboard will be mounted. You will need to extend the wires to reach a single location where the hoverboard will be mounted. The hoverboard is 2 by 4 inches and the motor connectors are located in one corner of the board. Pick a location for the hoverboard and determine the rough length of the each of the wires needed to reach this location.

Cut the existing thruster wires such that each end of the wires are at least 1 inch long. We will use the existing connectors on the thrusters and insert a segment of wire by soldering to make them longer. Soldering is an important skill that always comes in useful when working with embedded systems. In class you saw a demonstration of how to solder wires. This is the basic technique that you will use. All of the components on the hoverboards were soldered by hand using similar techniques.

Now cut a segment of red and black wire from the spools that will be long enough to enable the thrusters to reach the hoverboard location (note that it is better to have it slightly too long versus too short). Strip approximately a quarter inch of off of each end of all wires. Now "tin" each of the ends of all the wires, as was demonstrated in class. Tinning is the process of applying solder to the wires.

Now place the tinned wire ends together, perhaps having someone else hold them for you. Heat the wires and apply a little more solder so that they are fully soldered together. Once you have soldered all the joints, have someone else look at them and verify that the look well soldered. Remember that there should be solder over all the wire, there should be significant overlap of the wires, and the solder should be smooth, without sharp points. Once someone else verifies that the joints look good, use electrical tape to tape all of the wires so that nothing is exposed.

It is said that robotics is the "science of cables and connectors." Double check that all connections are good, otherwise you may run into trouble later when a thruster stops working for an unknown reason. It also may be a good idea to test each individual thruster before and after adding the extension to verify that they function.

Everyone in your group should solder at least one thruster.

5 Hovercraft Experiments

Now that you have designed and assembled your hovercraft, it is time to test how well it lifts. Note that you may find that you need to redo your skirt if the performance is not very good. Typical problems include loud vibrations, high friction, or air gushing out of one side or another. Sometimes it is possible to fix these problems by adding or removing weight from the hovercraft or adjusting the balance.

Question: Report on how well the skirt of your hovercraft works. Did the first version work? If not, what were the problems and how did you overcome them?

5.1 Powering Thrusters

Note, the thrusters are somewhat inexpensive and I have found that they may die if run consecutively for longer than 10 minutes at a time. Try to limit using the thrusters to times when you actually need to use them. Do not leave them running if you are not actively performing experiments. The symptoms you will see if you do run them for too long are that the thrust output will decrease significantly or it will stop completely. I suspect that this is due to motor overheating, although it could be caused by other problems (e.g. worn brushes). Let me know if any of your motors fail and please try to describe the usage characteristics.

As we are not yet using the Hoverboard, we will be using a power supply to power the thrusters. Before powering a thruster connected to the hoverboard, we will power a thruster that is not connected to anything. If you have already connected all of your thrusters, temporarily remove one for these experiments.

The power supplies have a maximum current rating of 2.5A and go up to 30V. You should start by setting the voltage to 8.4V. This is near the voltage of the batteries that we will be using later in the course. A number of extension cables have been provided that enable connecting the power supply to the thrusters. Without the thruster connected to anything, locate one of the extension cables and plug the red wire into the positive (+) terminal of the power supply and the black wire into the negative (-) terminal. Most systems use red to indicate positive voltage and black to indicate negative, however, this is just a convention so do not rely on it.

Question: The thrusters have a rated power of about 41W at 8.4V. How many Amps do they draw? The power supply cannot supply this much power.

With the voltage set to 8.4V, set the current control nob to a middle position. Have one person hold the casing of the thruster firmly, keeping fingers away from the blades. Another person should then connect the thruster to the power supply, red-to-red and black-to-black. Note that there may be a small spark and the motor will "jump" as it turns on.

Question: What is the voltage and current reading on the power supply? How much power is the motor using?

Disconnect the thruster from the power supply. Repeat this experiment with different (higher and lower) current limits.

Question: Record the voltage and current for a number of settings and report this and the total power usage. What is the minimum current that enables the motor to turn on?

Now, set the current limit the maximum and repeat these experiments by varying the voltage from 0.0V to 8.4V.

Question: Report your findings for these experiments. Explain the similarities or discrepancies from the initial experiment.

Question: Is all of the power converted into thrust? Where does the rest go?

5.2 Lift Experiments

Now, instead of connecting the power supply to a thruster you are holding, connect it to the main lift thruster. Start with a power setting just slightly above the power needed to start the motor. Slowly increase this until the hovercraft glides smoothly on your workbench surface. Note that if you have problems (excessive vibration, high friction, air venting, etc.), you may need to redistribute the weight on your hovercraft, increase the weight, or redo your skirt.

Question: How much power do you need to supply to the lift thruster to create low friction hovering on your workbench? How about when it is on the carpet or other surfaces?

There are pulleys, string, and weights (lots of nails that you can measure with the scale, please put them back in their boxes when you are done) in the lab. We will use these to characterize the forces needed to move the hovercraft with different lift power and different payload weights. Connect one end of the string to the hovercraft, thread the other end through the pulley, and finally connect the other end of the string to a weight. By holding the pulley at the edge of the table, you can drop the weight and determine the minimum weight needed to move the hovercraft. You can also time how long it takes to move the hovercraft a fixed distance.

Question: Perform a number of trials to characterize the performance of the hovercraft. Use different weights to pull the hovercraft, different lift thrust levels, and try adding more weight to your hovercraft (e.g. place a book on top of it without covering the lift thruster). Which lift thrust level results in the least friction? Does it continue to decrease when you increase the thrust, or does it level off? Discuss the results of all of these experiments and include any descriptive plots.

Question: (not required) Compute the friction of the hovercraft for various thrust levels. Please show work and describe your reasoning.

Question: (not required) Repeat some of these experiments on different surfaces.

5.3 Thrust Experiments

These experiments will require two power supplies. Use one to power the lift thruster at a level of low friction and the other to power one of your translational thrusters. Remember to disconnect the lift thruster when you are not actively performing experiments. Also, do not run it for longer than 10 minutes at a time without a few minute break. This will help to prevent damage to the thrusters.

In these experiments we will continue to use the rope, pulley, and weights, but now we will use them to characterize the translational thrusters. Start with the weight near the ground and the hovercraft near the pulley with the rope connected near the translational thruster you will be testing. Now engage the thruster.

Question: How much weight can the thruster lift? What about at different thruster power levels? Convert this into a thrust force, assuming zero friction, by determining the maximum weight that the hovercraft can move and recall $F = ma$ and on earth $a = g = 9.81 m/s^2$.

Now we will characterize the rotational speed of your hovercraft. Time how long it takes to rotate a full rotation clockwise and counterclockwise. For accurate results you may want to repeat this several times and/or count how long it takes to achieve multiple rotations.

Question: Report and analyze the results of your rotational experiments at different thrust levels.

Question: Does the hovercraft translate when you do this? If so, do you think it will be possible to compensate for this using the translational thrusters?

Question: Is the rotational speed constant? Or does it increase over time? Is there a maximum rotational speed? Does it achieve this quickly or slowly. For example, is the rotational speed just as fast in the first quarter turn as it is in the last quarter turn?

Question: Does the rotational speed change on different surfaces?

6 To Hand In

You should designate one person from your group as the point person for this lab (each person needs to do this at least once over the semester). This person is responsible for organizing and handing in the report, but everyone must contribute to writing the text. You should list all group members and indicate who was the point person on this lab. Your lab should be submitted by email before the start of class on the due date. A pdf formatted document is preferred.

Your lab report should have an introduction and conclusion and address the various questions (highlighted as ***Question:***) throughout the lab in detail. It should be well written and have a logical flow. Including pictures, charts, and graphs may be useful in explaining the results. There is no set page limit, but you should make sure to answer questions in detail and explain how you arrived at your decisions. You are also welcome to add additional insights and material to the lab beyond answering the required questions.

N.B. This is part (a) of Lab 1. You should complete a single lab report for all of Lab 1. However, you should start writing your lab report now, do not wait until you have completed all of the lab.

Question: You should make sure to include a picture of your final hovercraft.

Question: Robots like to have names, what are you going to call your hovercraft?

Question: For everyone in your group how many hours did each person spend on this part and the lab in total? Did you divide the work, if so how? Work on everything together?

Question: Please discuss and highlight any areas of this lab that you found unclear or difficult.

7 Appendix: Material Availability

Most materials (foam, brackets, screws, etc.) are available at any hardware store. The 5mil plastic, used for the skirt, is available in a number of places, however, I found that the 5mil plastic available at Ace Hardware on rolls (cut to length, intended for covering windows) is the right thickness and flexibility for the skirt. Other plastics tended to vibrate. I am not sure the exact type of plastic (as it was not labeled in the store), but I have found it in a number of Ace Hardware stores in a variety of states.

The thrusters (ducted fan EDF40) were purchased online at towerhobbies.com and are part number GWSG4000 or L5HHN906. They may be available other places and there are certainly other ducted fans that work well. A good alternative for a lift motor is an air mattress pump, although most are larger than the ducted fans. The same hovercraft design can be enlarged fairly easily to carry a person in which case a leaf blower works well as a lift pump (and thicker skirt plastic may be needed).